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ScienceDirect
Energy Procedia 85 (2016) 383 – 389
Energy Procedia

Sustainable Solutions for Energy and Environment, EENVIRO - YRC 2015, 18-20 November 2015, Bucharest, Romania

Breakup of Liquid Jets

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Abstract

The present paper investigates breakup of immersed jets of water and water - glycerol solutions in a hydrophobic environment. Organic oil was used as the surrounding medium. Experimental setup allowed the investigation of jet behavior, respectively the exact moment when perturbations appear. The phenomenon of jet breakup was quantified by measuring the breakup length. Maximum breakup length, normalized with the nozzle diameter, was plotted and analyzed function of dimensionless numbers. Results showed that normalized breakup length has a linear dependence with Reynolds and Capillary, respectively.

Peer-review under responsibility of the organizing committee EENVIRO 2015
Keywords: Immersed jet; Rayleigh instability; interfacial tension; breakup length

1. Introduction

Oil spilling pollution is one of the most important ecological problems of the century. Breakup of liquid jets is a phenomenon related to this problem. When oil is spilled in the ocean, generally it spreads at the water surface and, depending on its density and composition it might migrate into the water or form a slick at the surface [1]. This oil - water interaction leads to a process in which sea water droplets become suspended in the oil to form a water-in-oil emulsion. This physical mixing is promoted by turbulence at the sea surface and it increases the volume of pollutant between 3 and 4 times [2]. This affects drastically the evolution of the marine biosystem and it is a tremendous challenging problem for bioresearchers [3].

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Peer-review under responsibility of the organizing committee EENVIRO 2015
doi:10.1016/j.egypro.2015.12.265

In the environmental context of nowadays, understanding how pollutants are acting provides the main knowledge for finding optimal solutions to counteract their action. In this framework we are interested to see how droplets are formed when water penetrates a hydrophobic fluid, such as oil.

Along with the emulsification, other multiphase processes in which breakup of jets is of huge interest are widely encountered in nature, technology and basic science, such as medical diagnostics, DNA sampling, cosmetics, sprays, jet engine technology and combustion processes [4].

A liquid jet emerging from a nozzle will experience instability and breakup into drops. This phenomenon is known as Rayleigh instability. This instability is due to the interaction between the fluid discharging from the nozzle and the surrounding medium properties. The resulting shape of the interface can be a subject of Fourier analysis, and it can be showed that there is a certain wave length at which jet breakup occurs [4]–[6].

Until now, breakup of both Newtonian and non-Newtonian jets into droplets was extensively studied in the literature, covering mostly their evolution in the air [7]–[9]. Both theoretical and experimental aspects regarding the injection of a liquid jet in a gaseous medium were first studied by Lord Rayleigh [4], [10] .

The aim of this work was to investigate instabilities and breakup of different immersed jets into an oil phase. The influence of physical properties, such as viscosity, on the dynamics of breakup, especially the breakup length was discussed. Starting from Tomotika's work [5], a theoretical prediction for the breakup length was achieved, in good agreement with the experimental work.

Nomenclature

$\boldsymbol{\gamma}$	interfacial tension $[N/m]$
$\boldsymbol{\rho}$	density $[kg/m^3]$
$\boldsymbol{g}$	constant of gravity $[m/s^2]$
η	viscosity of water and water – glycerol $[Pas]$
$\boldsymbol{\eta_{oil}}$	viscosity of the surrounding medium $[Pas]$
$\boldsymbol{a}$	capillary length $[m]$
$\boldsymbol{D}$	needle inner diameter $[m]$
$\boldsymbol{R}$	needle inner radius $[m]$
$\boldsymbol{L}$	breakup length of the jet $[m]$
$\boldsymbol{v}$	single jet velocity $[m/s]$
$\boldsymbol{k}$	wave number $[1/m]$
$\boldsymbol{\lambda}$	wavelength $[m]$
$\boldsymbol{\omega}$	perturbation frequency (growth rate of disturbance $[1/s]$
$\boldsymbol{t}$	breakup time $[s]$

2. Materials and methods

The experiments involved in this study used organic oil as hydrophobic medium. Mixtures of water and glycerol were used for studying jet formation and breakup into oil. Pure water jet was used as reference.

By adding glycerol in water we increased the viscosity and density of the mixture.

Interfacial tension between the two phases was measured with the pendant drop method. Densities are evaluated by weighting a volume of liquid using a Hamilton microsyringe (Gastight #1725 0.25 ml) and a microscale balance (Radwag AS 82/220.R2). Viscosity was measured with a rotational rheometer (Anton Parr Physica MCR301), using a cone –plate geometry (CP 50/1°). Fluids properties are presented in Table 1, along with the capillary length, a, values. All fluids were tested at $25^{\circ}C$.

$$a = \sqrt{\frac{\gamma}{\rho g}} \tag{1}$$

Table 1. Liquids' Properties at $25^{\circ}C$

Glycerol concentration [%]	η [Pas]	γ [N/m]	ρ [kg/m^3]	a [mm]
0	1.00E-03	0.03	1004	1.75
40	0.00412	0.032	1117	1.71
50	0.00845	0.028	1149	1.58
60	0.0131	0.029	1177	1.58
Oil	0.055	-	877.5	-

Experimental setup, sketched in Fig. 1 consists of a glass cell filled with organic oil, a syringe pump and a high-speed camera (Nikon J5). Two different needles with the interior diameters $D_1 = 0.838$ mm (code) and $D_2 = 0.514$ mm were connected to the syringe pump, as indicated.

Jets of water in oil were created injecting water throughout the needle at different flow rates. Flow rate was chosen from $5ml/min$ to 30 ml/min, limited by the syringe pump to prevent the motor to stall.

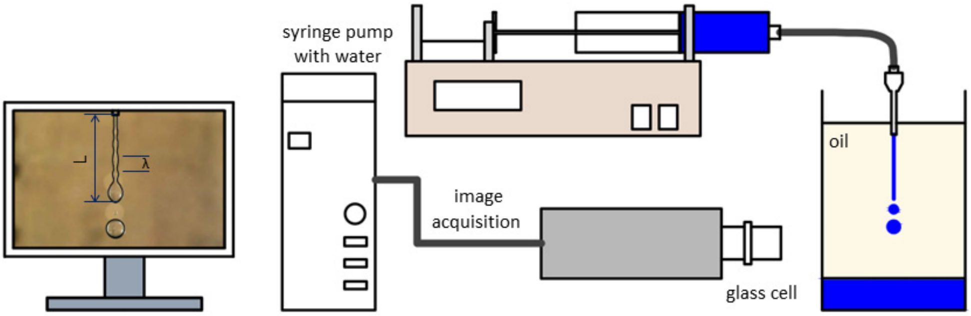

Fig. 1 – Sketch of the experimental setup. Exemple of water jet in oil and measurement of breakup length L

The progressive thinning of the thread is driven by capillarity and resisted by inertia and viscosity. The velocity between the jet and the surrounding liquid (oil) is different. Thus, the oil- water (or glycerol – water mixture) is unstable [4].When the jet column shape becomes unstable it eventually breaks into drops. Breakup length, defined by Eggers and Villermaux, represents the minimum distance from the nozzle over which the liquid jet is still connected [4]. In our studies we measured the maximum breakup length, L, as indicated in Fig.1. All experiments were performed at $25^{\circ}C$ in triplicate and representative images were chosen for analysis.

3. Results and discussion

3.1. Image analysis

Movies at normal and high speed were recorded from a perpendicular direction to the jets plane. Fig. 2 shows a set of photos of water jet in oil. Rayleigh instabilities of the water jet were observed. Wavelength can be distinguished in the images. The jet's lead has a round shape, prior to drop formation. The volume of this drop in increasing, then breakup occurs. The same behaviour and response was also observed in the case of glycerol – water mixtures.

Dimensionless numbers, Reynolds and Capillary numbers, were calculated using of jet velocity throw the needle. These numbers were used for further determination of the jet breakup dynamics.

Re – ratio of inertia and viscous forces:

$$Re = \frac{\rho v D}{\eta} \quad (2)$$

Ca – ratio of viscous forces to interfacial tension:

$$Ca = \frac{\eta v}{\gamma} \tag{3}$$

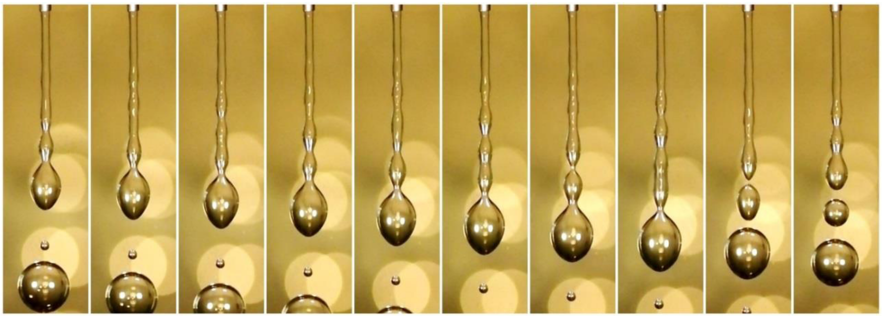

Fig. 2 – Breakup of water jet in oil; velocity 10 ml/min; needle diameter 0.838; each two frames are separated by 40 ms

3.2. Parameter L/D dependence

Maximum breakup length, L, was measured from image data. It was normalized with the needle diameter, D. Re and Ca number were calculated for three different glycerol concentration in water, 40%, 50% and 60%, respectively. Experimental data for L/D parameter, normalized breakup length, were plotted function of Re and Ca number (Fig. 3 and Fig. 4.). Normalized breakup length has a linear dependence with these two dimensionless numbers.

Viscosity was increased by adding glycerol in water. The exact impact on breakup length was analysed for different jet's flow rate. Fig. 5 represents the variation of parameter L/D with increasing viscosity. A decreasing nonlinear effect on liquid breakup length can be noted.

Results presented were for the same nozzle diameter. Fig. 6 represents the normalized length function on Re number for two different nozzles interior diameters (0.838 mm and 0.514 mm). Jet breakup shows similar behaviour for certain Re. Same behaviour was noticed for other glycerol concentrations.

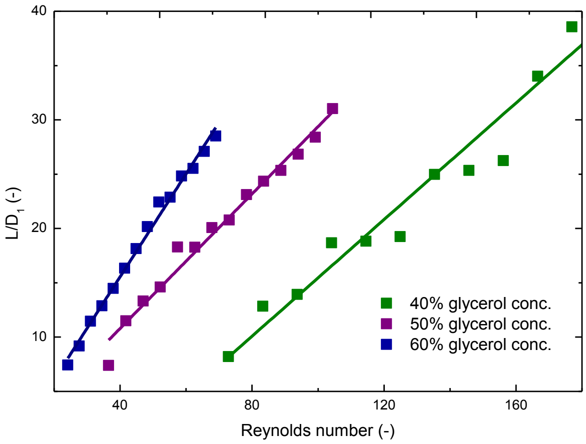

Fig. 3 – Dependence $L/D_1(Re)$ for three different glycerol concentrations in water

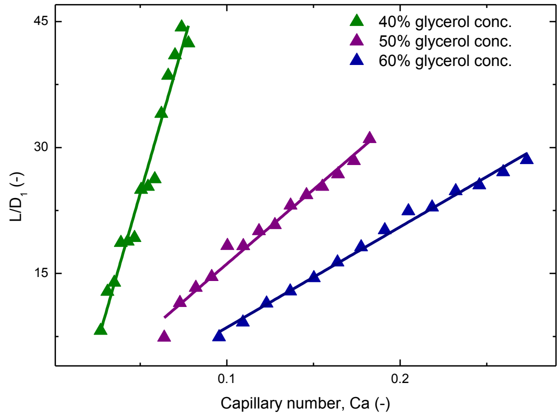

Fig. 4 – Dependence $L/D_1(Ca)$ for three different glycerol concentrations in water

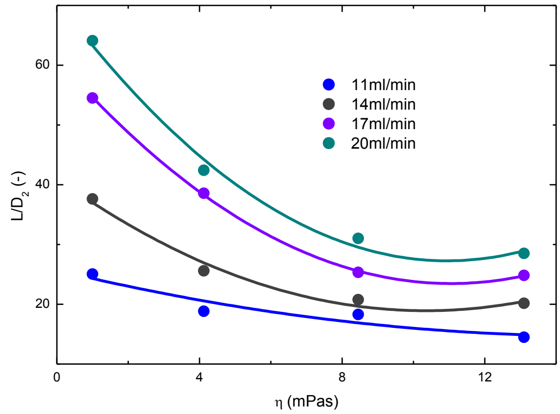

Fig. 5 - Parameter L/D_2 dependence with viscosity at constant flow rate (viscosity increasing with increasing glycerol concentration in water)

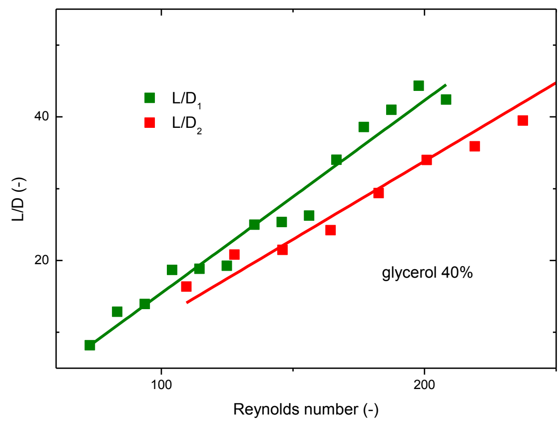

Fig. 6 – Dependence $L/D(Re)$ for two different needle diameters ($D_1 = 0.838\ mm$ and $D_2 = 0.514\ mm$); glycerol 40 % concentration in water

3.3. Theoretical prediction of breakup length, L

The breakup phenomenon is characterized by the breakup length, L, and the dominant wavelength, λ, that causes formation of droplets. One of the hypotheses that Tomotika considered was a cylindrical thread of viscous fluid surrounded by another viscous liquid [5]. Considering that inertial effects are small against the viscosity, he derived a dispersion relation that captures the dependence of perturbation frequency (growth rate of disturbance [5]), ω $[1/s]$, on the wave number:

$$\omega = \gamma(1 - k^2R^2)F(kR)/(2R\eta_{oil}) \tag{4}$$

where the wave number, $k = \frac{2\pi}{\lambda}$, and $F(kR)$is a function of kR resulting from the equation of motion.

As described in [5], Tomotika's dispersion relation (4) was analyzed. Breakup occurs for the maximum wavelength. The wavelength, λ , that theoretically predicts breakup, can be determined. For that, $F(kR)$ needs to be plotted. In Fig. 7 values of $(1 - k^2R^2)F(kR)$ were plotted for different water-glycerol solutions in order to extract information regarding the curve shape for these specific cases.

Increasing viscosity shifts the maximum growth rate of breakup to lower values and to shorter wavelengths. The next step was to determine a relation that predicts the breakup length, considering that:

$$L = vt$$

$$t = C/\omega_{max}$$

$$L = Cv/\omega_{max} \tag{5}$$

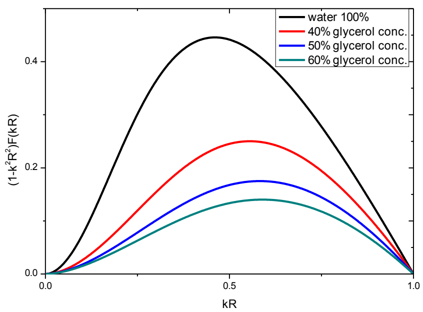

Fig. 7 – Tomotika's dispersion relation for three different glycerol concentrations in water and water, respectively

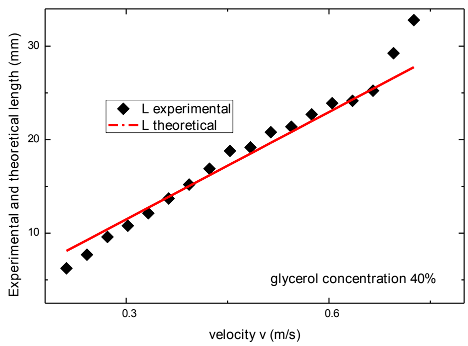

Fig. 8 – Experimental and theoretical prediction of length L for 40% glycerol concentration in water

Instability occurs for values of $kR < 1$. Wavelength that produces breakup corresponds to the maximum value of $(1 - k^2R^2)F(kR)$, predicted in Fig. 7. Maximum wavelength $\omega_{\max}$ was determined from (4) and applied for jet breakup theoretical prediction (5). Experimental data were compared with theoretical predictions for solutions with 40% glycerol (Fig. 8). The value of the constant C [5] is found to be 3.49. This constant depends on both initial and maximum amplitude of perturbation.

4. Conclusion and future work

An experimental work has been performed in order to study viscosity influence, ratio between jet viscosity and surrounded fluid viscosity, respectively, on the dynamics and breakup of jets. Organic oil was used as a surrounding medium. Jets of water in oil were created. Viscosity of the jets was increased by adding glycerol in water (40%, 50% and 60%).

As expected, increasing viscosity and density of the jet has a decreasing effect on breakup length. Parameter L/D, representing normalized breakup length with the diameter of the nozzle, was analysed function of dimensionless numbers, Re and Ca.

Dispersion relation derived by Tomotika [5] was the input in theoretical prediction for breakup length. Further investigation of C constant has to be made, the precise variation of C with increasing viscosity. The manner in which this constant varies from one solution to another needs further investigation. For a lower glycerol concentration, for example, 50%, C was found to be 4.74. Experimental data and theoretical predictions were found to be in good agreement for the first jet investigated (40% glycerol concentration in water).

Atomization of immersed jets in oil, transition from Rayleigh regime to atomization, is another subject of our future work.

Acknowledgements

The work has been funded by the Sectoral Operational Programme Human Resources Development 2007-2013 of the Ministry of European Funds through the Financial Agreement POSDRU/159/1.5/S/134398 and POSDRU/159/1.5/S/132395.

The authors acknowledge the financial support from the grant CNCS-UEFISCDI: PN-II-PT-PCCA-2011-3.1-0052 and PN-II-ID-PCE-2012-4-0245.

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